Proceedings of ITEA
International Test and Evaluation Association
Modeling and Simulation Conference
December 11-14, 2006, Las Cruces, New Mexico

AN EXAMPLE FOR INTEGRATED GAS TURBINE ENGINE TESTING AND ANALYSIS USING MODELING AND SIMULATION*

Milt Davis and Dave Beale
Aerospace Testing Alliance
Arnold Engineering Development Center
Arnold Air Force Base, TN 37389-9013

Lt. Col. Keith Boyer and Maj. Devin O'Dowd
Department of Aeronautics
United States Air Force Academy
Colorado, Springs, CO

ABSTRACT

With increasing emphasis on streamlining the acquisition process, ground-test centers like AEDC are re-evaluating their roles in the development of aerospace systems. Instead of the traditional role of merely providing data from ground-test facilities, the new emphasis challenges the Center to become a team member that provides ***knowledge for risk management and decision making*** during the development and operation of an aerospace system. As a key link in the transition from a laboratory or design concept to an operational system, the capabilities of a ground-test center can provide a tremendous opportunity to reduce the time and cost involved in flight vehicle system development. AEDC has aggressively accepted the challenge and has developed an ***Integrated Test and Evaluation*** (IT&E) approach to support aerospace system development efforts. This paper focuses on an integrated test and evaluation process embraced by AEDC and the USAF Academy in a joint test and analysis effort of the F109 turbofan engine. This process uses a swirl investigation as a vehicle to exercise and demonstrate the approach.

INTRODUCTION

The integration of the airframe and its propulsion system is a key design issue in the development and deployment of military aircraft. Many disciplines comprise this issue, one being the aerodynamic interaction between the inlet system and the engine. The external airframe and inlet system must capture flow from the freestream and deliver it to the installed engine at Mach numbers commensurate with fan or compressor requirements. Unfortunately, the modification of the flow to meet engine requirements generally results in flow distortion that can degrade engine performance, operability, and durability. Such degradations may include loss of thrust, loss of stability margin with the potential for surge or even flameout, and the reduction of fan or compressor life due to high cycle fatigue (HCF). Therefore, such degradations introduce serious issues both in the success of the weapon system during combat and in the cost of maintaining system readiness. Therefore, the aircraft developer must consider the compatibility of the inlet and the engine throughout the design process.

For over 30 years, the Society of Automotive Engineers (SAE) S-16 committee (Turbine Engine Inlet Flow Distortion Committee) has been providing methodologies and standards for the aircraft/engine community to use in testing and analyzing inlet distortion effects on gas turbine engines, focusing on the performance and operability aspects of inlet-engine compatibility. Using the existing SAE S-16 methodologies, inlet distortion has traditionally been characterized by consideration of total pressure distortion, total temperature distortion, or planar waves, either singularly or in combination [1, 2, 3, & 4]. However, many gas turbine installations can generate significant flow angularity as well as total pressure distortion at the Aerodynamic Interface Plane (AIP). These issues prompted the SAE S-16 Committee to embark on the development of a methodology for considering swirl as part of the inlet-engine compatibility assurance process.

In the mid 1990's the Arnold Engineering Development Center (AEDC) embarked on the development of distortion generation technologies for use in direct-connect tests [5]. In parallel, AEDC has also embarked on the development of turbine engine numerical simulations capable of predicting the response to inlet distortion [6, 7, 8]. These developments were motivated by the goal of developing an inlet-engine compatibility methodology that integrates test and computation to realize the benefits of both. Initially, these developments focused on the effect of total pressure distortion on operability and performance. Currently, this work both experimentally and computationally is focusing on the influence of swirl distortion on operability and performance and is expected also to consider the analysis of aeromechanical response.

Turbine engine tests with inflow swirl are needed to enable the development of methodologies of assessing inlet-engine compatibility. As a result, AEDC and the United States Air Force Academy (USAFA) initiated a project that will apply swirl distortion generators under development at AEDC to the

*The research reported herein was performed by the Arnold Engineering Development Center (AEDC), Air Force Materiel Command. Work and analysis for this research were done by the personnel of Aerospace Testing Alliance (ATA), the operations, maintenance, information management, and support contractor for AEDC. Further reproduction is authorized to satisfy the needs of the U.S. Government.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **DEC 2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**

4. TITLE AND SUBTITLE **An Example for Integrated Gas Turbine Engine Testing and Analysis Using Modeling and Simulation**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Arnold Engineering Development Center,Aerospace Testing Alliance,Arnold AFB,TN,37389-9013**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
2006 ITEA Modeling and Simulation Conference, Dec 11-14, 2006, Las Cruces, NM

14. ABSTRACT
With increasing emphasis on streamlining the acquisition process, ground-test centers like AEDC are re-evaluating their roles in the development of aerospace systems. Instead of the traditional role of merely providing data from ground-test facilities, the new emphasis challenges the Center to become a team member that provides knowledge for risk management and decision making during the development and operation of an aerospace system. As a key link in the transition from a laboratory or design concept to an operational system, the capabilities of a ground-test center can provide a tremendous opportunity to reduce the time and cost involved in flight vehicle system development. AEDC has aggressively accepted the challenge and has developed an Integrated Test and Evaluation (IT&E) approach to support aerospace system development efforts. This paper focuses on an integrated test and evaluation process embraced by AEDC and the USAF Academy in a joint test and analysis effort of the F109 turbofan engine. This process uses a swirl investigation as a vehicle to exercise and demonstrate the approach.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**10**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

determination of engine response in terms of aeromechanics, operability, and performance. The tests will serve the turbine engine community by helping to identify the role that distortion might play in HCF failures, providing the SAE data to help substantiate swirl descriptors under consideration, and providing a data set for validating compression system and engine models under development.

The collaborative AEDC-USAFA swirl project entails adapting AEDC bulk and twin swirl distortion generator test apparatus to an F109 engine test stand in place at USAFA. During the test, engine operability in terms of stability margin, and aeromechanics in terms of blade vibrations will be measured as the engine is subjected to swirl. The project also entails computationally modeling the fan. This includes applying newly developed models to pretest predictions of operability and model validation using test data. Containing test and numerical modeling, the project offers the opportunity to demonstrate the integration of test and computational models.

This paper focuses on an integrated test and evaluation process embraced by AEDC and the USAF Academy in a joint test and analysis effort of the F109 turbofan engine, an effort which uses a swirl investigation as a vehicle to exercise and demonstrate the approach. The following sections provide a definition of the IT&E process and descriptions of the test plan, the modeling plan, and the combination of these elements into an IT&E process that synergizes the attributes of each.

ENVISIONED INTEGRATED TEST AND EVALUATION PROCESS

A multidimensional conceptual model of the IT&E approach is illustrated in Figure 1. In the simplest sense, IT&E might involve the use of computer modeling tools (such as computational fluid dynamics or engineering methods prediction codes) only to augment or correct test data acquired in a wind tunnel or an engine test cell.

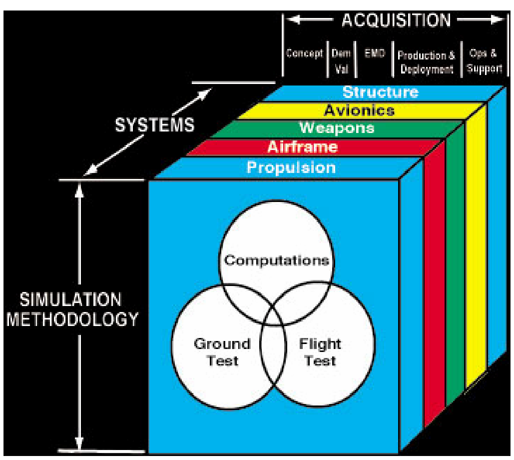


Figure 1. Integrated Test and Evaluation Concept

However, integrating the modeling and simulation (M&S) tools directly with ground and flight tests enables one to design a better ground-test program, validate the ground-test results, extrapolate the results to flight conditions, and assist in decision making for a more efficient or effective flight-test program.

Looking at the second dimension of the conceptual model, one finds that IT&E takes on a more important role when used to integrate airframe, propulsion system, weapons, avionics, and other flight vehicle subsystems. Without IT&E, the airframe would be developed and the engine added serially. Moreover, the weapons would likely be added "after the fact." Consequently, one might be well into the flight-test program before serious integration problems become apparent. Fortunately, it is possible today to apply the IT&E approach, which involves concurrent ground tests of multiple flight vehicle subsystems, to accelerate and improve the integration of those subsystems before flight.

The joint effort between AEDC and the USAF Academy provides an excellent vehicle to put into practice an IT&E process that can be used as an example for future test organizations to follow. Illustrated in Figure 2 is the envisioned process that will be used with the F109 test and analysis program.

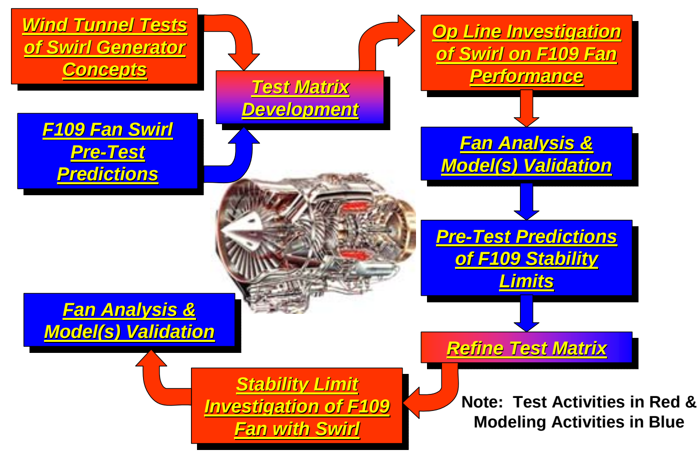


Figure 2. Integrated Test and Evaluation Process for the F109 Swirl Test Program

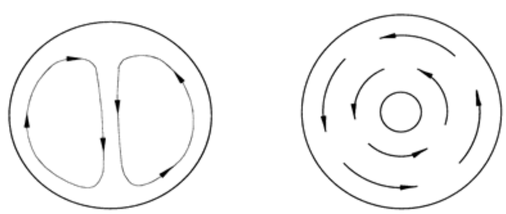
Using the combination of what the generators can produce and an estimate of the effects of swirl on the F109 fan, a test matrix can be developed that will provide the framework for the swirl test program. It is envisioned that the first set of tests will only investigate the effects of bulk and twin swirl on the fan at the operating point (i.e. no back-pressuring device will be required). This test will provide information as to the engine performance change due to swirl and will provide information to partially validate the fan models. Once the models have been updated to the test condition, they can be used to make predictions of the fan's operability characteristics. These predictions will be used to refine the test matrix, which will then be used to define the next series of tests, tests that will use a back-pressuring device. A final model validation will then be conducted using the operability information, thus providing a model of the fan of the as-tested F109 engine.

There are several products that are associated with this joint effort. Directly, swirl generator concepts will be tested in an engine environment. Experience will be gained as to the swirl generator concept and how well it performs. Swirl effects on engine/fan performance and operability will be investigated and data generated for use with future systems that may have a significant amount of swirl associated with the inlet. Numerical simulations of the fan will be validated for use in future endeavors. A major product will be the demonstration of an Integrated Test and Evaluation process that can be a model for future test and analysis efforts. The following sections provide definitions of inlet swirl and descriptions of the test and numerical simulations that will be applied in the IT&E demonstration.

SWIRL IN AIRCRAFT INLET SYSTEMS

A defining mark in the evolution of manned fighter aircraft and Unmanned Combat Air Vehicles (UCAV) is the advent of stealth. Although inlets designed for stealth effectively hide the engine face from enemy radar detection, they also introduce configurations, such as S-ducts, known to produce swirl. Reference 5 includes descriptions of three types of swirl: (1) paired swirl, (2) bulk swirl, and (3) tightly wound vortices. This investigation focuses on paired swirl and bulk swirl, which tend to form in S-ducts featured in stealth inlets as well as in the inlets to auxiliary power units (APUs).

Paired swirl is produced when a flow containing vortices normal to the flow direction is turned in the plane of the vortices. Paired swirl is the most common case of swirl and is associated with flow in an S-duct. Low velocity fluid moves inward in boundary layers at the left and right of the duct (when the turn is in the vertical plane). This results in two vortices rotating in opposite directions at the exit of the turn. When the two vortices have equal magnitude and opposite rotation, this is termed twin swirl. Twin swirl has zero circumferential average around the annulus. In the more general case of flow with nonsymmetric boundary layers, the flow results in two vortices of opposite rotation but different magnitude. In this case, the swirl has non-zero circumferential average around the annulus. A schematic of paired swirl appears in Figure 3.



a. Paired Swirl **b. Bulk Swirl**

Figure 3. Types of S-Duct Swirl

Bulk swirl is a special case of paired swirl in which the magnitude of one of the swirls greatly exceeds that of the other. It is shown schematically in Figure 3. Bulk swirl resembles a solid-body rotation and is characterized by a non-zero average circumferential velocity around the annulus. In the case of aircraft inlets, bulk swirl is often produced in S-ducts with nonaxially symmetric total pressure gradients acting through the turn in the duct. S-bend-induced pressure gradients acting on a locally separated flow can result in bulk swirl. The swirl process may be initiated when a total pressure deficit region occurs out-of-plane with the bend (e.g., left and right for a vertical S-duct).

TEST PROGRAM

In the collaborative test program, AEDC is responsible for developing and providing the swirl generator, substantiated in precursor wind tunnel tests, while the USAF Academy provides the services of the F109 installed in a ground-test facility [9]. To execute this approach, AEDC modified its technology development program to allow interfacing the concept test hardware to the engine test installation. Modifications included not only matching the physical dimensions of wind tunnel test apparatus with the F109 installation, but implementing steps in the design process that will mitigate any risks to the engine. Similarly, the Academy has instituted modifications to the F109 test stand to accommodate the swirl generator apparatus as well as instrumentation systems that will be required. The following section furnishes brief descriptions of the test apparatus and instrumentation systems that will be applied.

Swirl Distortion Generator Development

In the 1990s, AEDC initiated the development of distortion generators to address future performance, operability, and durability turbine engine direct-connect test requirements. The trends in combat aircraft capabilities that motivated the development are discussed in Ref. 5. To respond to the challenges that the turbine IT&E community faces, the AEDC development encompassed a number of distortion generators for use in direct-connect tests:

1. **Transient Total Pressure Distortion Generator**: Simulates transients in total pressure distortion that the engine experiences during combat aircraft maneuvers.
2. **Swirl Generator:** Simulates bulk swirl, paired swirl, and tightly wound vortices that may be encountered by high-performance maneuvering aircraft featuring stealth inlet systems.
3. **Total Temperature Distortion Generators:** Simulate hot-gas ingestion that may be experienced during release of bay-launched missiles, V/STOL hover operations in ground effect, and catapult steam ingestion.
4. **Turbulence Generator:** Simulates pressure fluctuations in support of HCF assessments.

AEDC adopted a five-step process to apply to the development of each distortion generator technology:

- **Step 1** – Establish distortion pattern simulation requirements
- **Step 2** – Identify distortion generator concepts
- **Step 3** – Select concept based on feasibility assessment and tradeoff study
- **Step 4** – Develop selected concept at component level
- **Step 5** – Develop and validate a fully functional prototype

Step 1 provides the distortion patterns and fidelity requirements that will later serve as validation criteria for the prototype distortion generators. **Step 2** provides a comprehensive list of candidate methods of generating the required patterns. **Steps 3 and 4** entail the application of CFD and test to evaluate the feasibility of candidate concepts for concept selection and to define the design of the selected concept components prior to the design of a prototype. Tests in these steps use low-cost, fixed-geometry test articles to address specific feasibility or component design issues. At this writing, the four distortion generators are in various stages of development.

The total pressure distortion generator development progressed through Step 5 and yielded a research prototype. The total temperature distortion generator and the turbulence generator are in the concept identification stage (Step 2). The swirl generator development is in Step 3. In this step, CFD and wind tunnel tests are being applied to five concepts that were down-selected from Step 2. These include concepts for producing bulk swirl, paired swirl, and tightly wound vortices. Rather than waiting for the completion of the progression through Step 5, the swirl test with the F109 will adapt wind tunnel apparatus selected from the Step 3 investigation. Although the concept test models will lack the remotely variable pattern capability planned for the fully functional prototype of Step 5, they will allow engine tests of specific bulk and paired swirl patterns to occur in parallel with the distortion generator development.

Two swirl generator concepts from the five under investigation were selected for consideration in the engine test program:

- Turning vanes for bulk swirl
- Swirl can for bulk swirl or paired swirl.

Each concept has been the subject of CFD investigations, and the mechanical design of test apparatus suitable for both the wind tunnel tests and the engine tests are under way at this writing. The selection of specific fixed-point distortion generators to be applied in the engine tests will depend upon results of the wind tunnel tests. The turning vane concept for bulk swirl resembles a set of IGV's fixed in the air supply duct upstream of the engine face as shown in Figure 4.

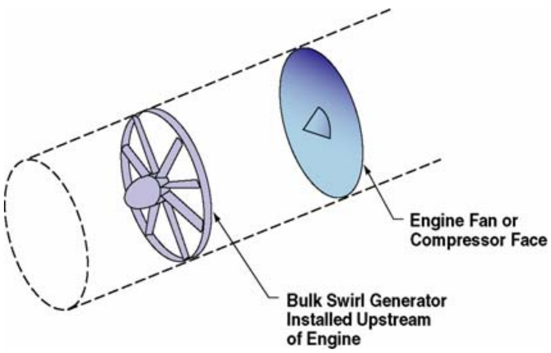


Figure 4. Turning Vane Concept for Bulk Swirl.

To provide remotely variable swirl in an operational swirl generator, the system would feature variability in vane incidence angle (with respect to the approaching flow) and effective vane twist angle. The CFD investigation focused on aiding the selection of blade geometry and evaluating methods of providing variable twist. A sample CFD result, which illustrates the bulk swirl predicted with the particular configuration, appears in Figure 5.

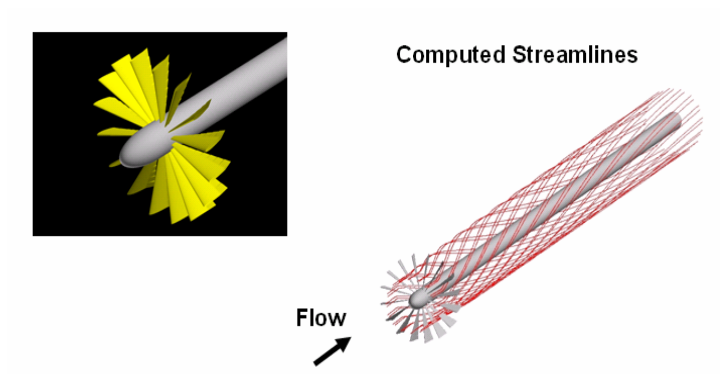


Figure 5. Computed Bulk Swirl Streamlines

The swirl chamber concept uses a different approach to inducing swirl. The swirl chamber consists of a cylinder mounted at the entrance to the engine air supply duct, in place of the normally used bellmouth. Air enters the chamber tangentially as shown conceptually in Figure 6 so that an internal circumferential flow is established.

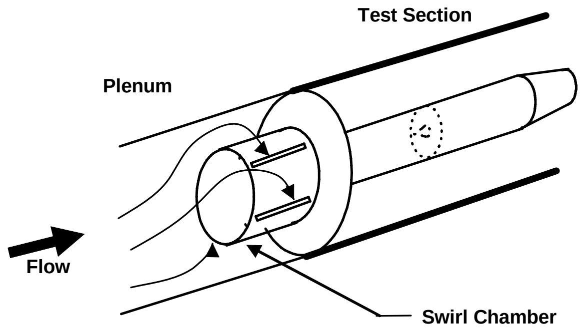


Figure 6. Swirl Chamber Concept

The flow then exits the chamber through an opening in the end of the cylinder and accelerates as it enters the engine air supply duct. The entrance openings can be configured to produce bulk or twin swirl patterns as shown in Figure 7. Computed streamlines for a bulk swirl configuration are shown in Figure 8.

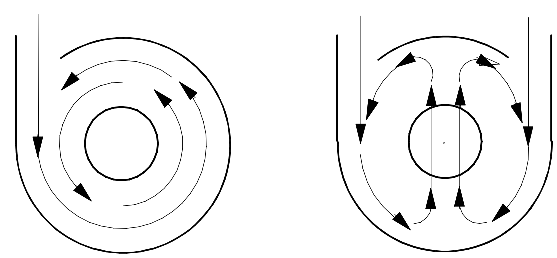


Figure 7. Swirl Chamber Configurations for Bulk and Paired Swirl.

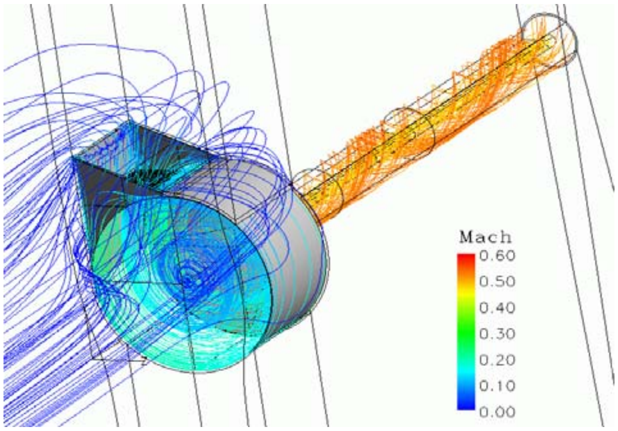


Figure 8. Swirl Chamber Computed Bulk Swirl Streamlines

The modifications of concept test to enable support of the F109 test were threefold. First, the test apparatus physical size was modified according to F109 requirements. This entailed increasing the size of the models to match the engine fan diameter of nominally 18.7 in. Second, the concept test apparatus was modified to interface with the USAFA F109 test site and test apparatus. For example, the apparatus included duct spool sections to house the distortion generator and the distortion measurement instrumentation while interfacing with the F109 and the bellmouth flanges. Third, the design effort was expanded in scope to safeguard the engine from foreign object damage (FOD). This entailed eliminating connections or moving parts in the flow stream, selecting materials that will minimize fatigue failure risks, and conducting formal stress analyses with suitable safety factors that mitigate the risk of structural failure. This also entailed adopting a thorough review process for the test apparatus mechanical designs enlisting experts both at AEDC and at USAFA.

Swirl Generator Wind Tunnel Test

The information sought in Steps 3 and 4 of the distortion generator development process requires tests that furnish parametric data to validate the CFD results and to facilitate the selection of configurations for the prototype. Although the concept test apparatus lacks the remotely controlled variable geometry components that will be employed in the prototype, it does feature modular designs that enable a large number of "builds" to be tested in experimental parametric studies. For example, the swirl chamber design features 16 overall combinations of diameter and length, 8 for bulk swirl and 8 for paired swirl. For bulk swirl, it also features an entrance slot width infinitely variable between limits selected on the basis of the CFD study. The wind tunnel tests of Steps 3 and 4 will be executed prior to the engine test so that they can be used to help select configurations for the engine test and in order to thoroughly characterize the distortion generator prior to shipment to USAFA.

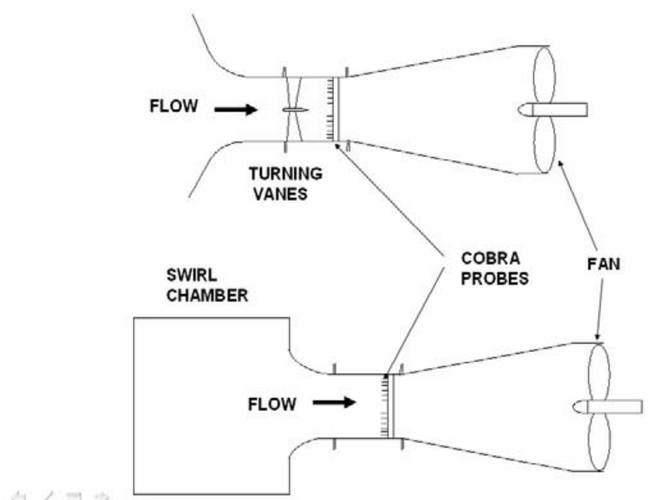


Figure 9. Generator Wind Tunnel Test Installations

The wind tunnel tests will be conducted in the Sverdrup Technology, Inc. wind tunnel (Tullahoma, Tennessee). The wind tunnel is an open-circuit facility that uses an atmospheric in-bleed and a pair of exhaust fans. For the purpose of the distortion generator tests, the wind tunnel plenum section and test section will be replaced either by the swirl chamber or, in the case of the turning vanes, by a bellmouth and circular duct. These installations are shown schematically in Figure 9. Cobra probes in the circular duct will provide the flow angle measurements needed to characterize swirl.

F109 Test with Swirl Generator

The F109 engine offers an ideal test article for the swirl tests since, lacking inlet guide vanes (IGVs), it represents an engine expected to exhibit a sensitivity to swirl distortion. Furthermore, the moderate physical size and airflow specifications allow full-scale distortion generator hardware to be characterized in a small research wind tunnel prior to the engine test.

The F109 is a turbofan engine with a bypass ratio of 5 and a maximum thrust of 1330 lbf. As shown in Figure 10, the engine features a single-stage fan, a two-stage centrifugal compressor, a reverse-flow annular compressor, a two-stage, high-pressure turbine, a two-stage, low-pressure turbine, and a common core flow/bypass flow nozzle. The fan diameter is 18.7 in., and the design corrected mass flow is 52.2 lbm/sec.

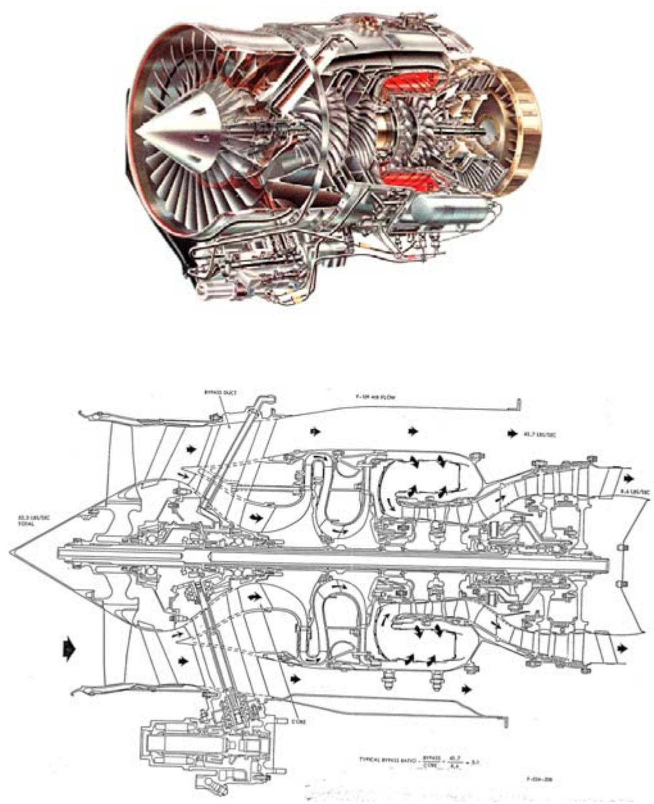


Figure 10. F109 Engine

The Academy possesses an indoor, atmospheric test stand with an F109 installation [9]. The installation includes an inlet bellmouth and an engine mount with a thrust stand as shown in Figure 11. The USAFA engine is equipped with approximately 200 instrumentation channels to measure and record gas flow path and engine health parameters. During the swirl test, this instrumentation will be augmented to furnish two additional types of information. First, cobra probes mounted in the adapter spool section, and used in the wind tunnel test, will be used to measure the swirl entering the engine. Second, a Non-Intrusive Stress Measurement System (NSMS) will be employed to measure the engine structural response to the swirl [10]. The

NSMS instrumentation provides measurement of time-variant blade deflections using probes mounted in the engine case that detect blade tip deflection during blade passage, as shown in Figure 12.

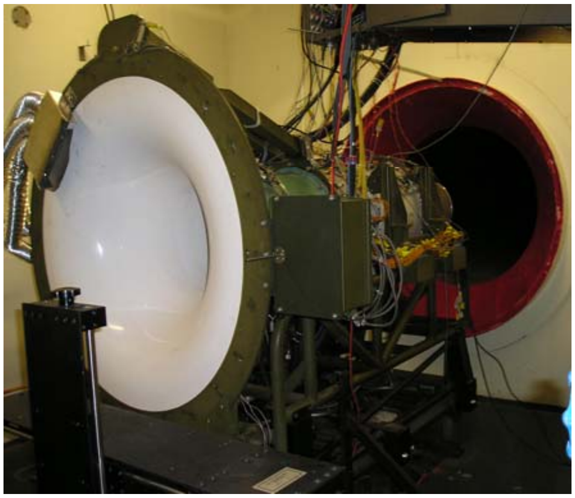


Figure 11. USAFA F109 Test Installation

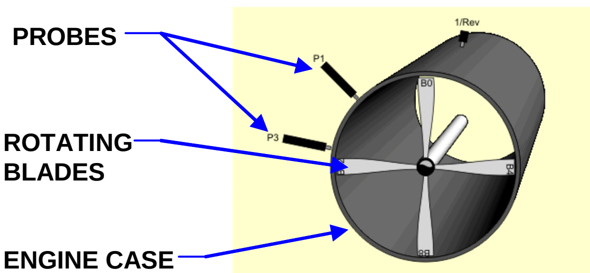


Figure 12. NSMS Measurement Technique

These blade vibration measurements can be used to infer the time-variant stresses on the blade. The test includes the NSMS system for two purposes. The first is to monitor blade aeromechanics to help protect the engine during the input of forcing functions that will likely induce blade vibrations. The second is to start a database characterizing engine structural response to swirl.

A number of modifications to the USAFA installation will be instituted to accommodate the swirl generator apparatus and instrumentation. Since the swirl generator concept test apparatus design includes the USAFA test installation as a requirement, most of the interface features are incorporated in the generator apparatus. The AEDC generator duct section will mate directly to the engine face flange. Therefore, mounting the distortion generator will require little more than removing the Academy bellmouth and duct and replacing it with the AEDC apparatus. Simple schematic diagrams of the swirl chamber and swirl vane installations appear in Figure 13

In addition, the operability tests will require a method of back-pressuring the fan in order to achieve conditions off the normal operating line. Historically, this has been accomplished by either perturbing cell pressure in altitude test facilities or by using a translating flow plug in ground-level facilities. The current test will employ the latter approach. A final modification that may be required is the addition of a case penetration for the NSMS probe. (Depending on the engine wall configuration, some probes can "see" the blade tip through the wall material and avoid an actual penetration.)

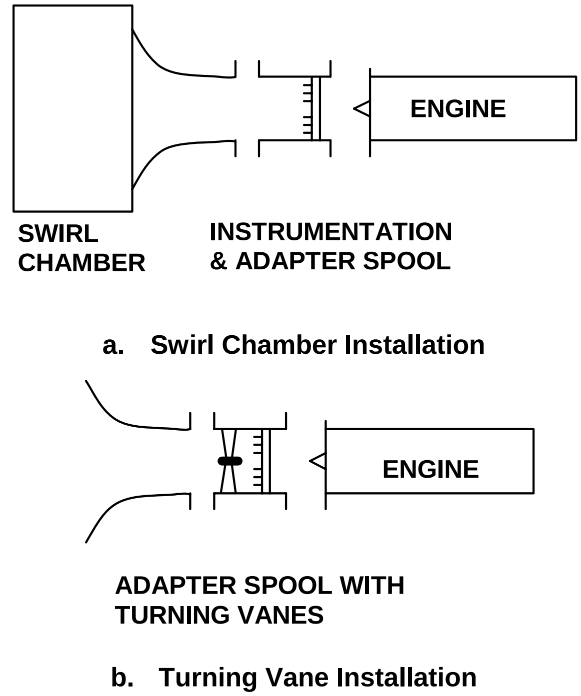


Figure 13. Schematics of Swirl Generator Installations

In addition to the blade vibration monitoring provided by the NSMS system, the engine system will be modified to help safeguard the engine from the potentially harmful effects of stall. The F109 is prone to rapidly enter a dangerous overspeed condition during fan stall events. The engine control system is designed to prevent this from happening. Therefore, the test will involve control system modifications that will allow fan stall to be approached while preventing an overspeed condition should a stall occur.

As suggested by the instrumentation description, the engine test will involve three types of measurements:

1. **<u>Performance:</u>** The USAFA F109 installation currently includes the instrumentation required to determine performance parameters such as thrust, fuel consumption, and pressure ratios.

2. **<u>Operability:</u>** The translating plug aft of the engine exhaust nozzle will be used to gradually decrease mass flow through the engine at a constant engine speed. The results will be used to help delineate the stability margin with and without swirl distortion present.

3. **<u>Durability:</u>** The measurement of fan blade vibrations in the presence of swirl will be used to provide the HCF community data on the effect of swirl on engine blade structures.

NUMERICAL SIMULATIONS FOR ANALYZING SWIRL DISTORTION

The effects of either paired or bulk swirl on compression system performance and/or operability can be analyzed using one of the following numerical methods, either by itself or in combination.

- Meanline analysis
- Parallel compressor analysis
- 3D Euler analysis

These modeling techniques are briefly described in this section to outline the rudimentary fundamentals of the modeling techniques. Each of these methods is presented in the following sections with an example of how each type of code can be used to analyze swirl effects. All of the examples come from previous investigations and use a simple rotor, Rotor 1B, and are reproduced in a brief form in this paper to give the reader an indication of the potential analysis capability of each code.

Meanline Analysis

The meanline analysis technique (model) is, in general, a compressible, 1-D, steady-state, row-by-row characteristics solver [11]. The purpose of the meanline model is to provide a rough estimate of the overall performance of a compression system that is characterized by the blade geometry at the mean radius. It is also beneficial because radial effects can be neglected, and therefore, the radii of the meanline streamline remains relatively constant as opposed to the radii of hub and tip streamlines. The meanline code uses elementary velocity diagram expressions along with empirical blade loss (ω') and deviation (δ) correlations to move from the ideal (textbook theory) to estimating real effects as illustrated in Figure 14.

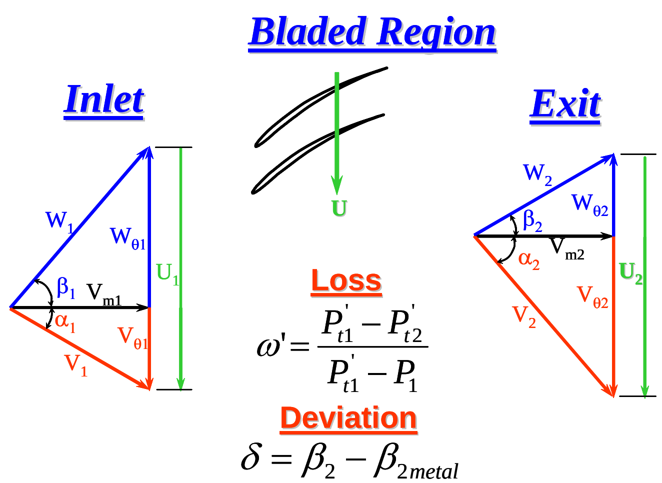


Figure 14. Meanline Theory Using Velocity Diagrams

Where:

- P_t' represents total pressure in the relative frame
- P represents static pressure
- α represents absolute velocity angles
- β represents relative velocity angles
- W represents relative velocity magnitudes
- V represents absolute velocity magnitudes
- U represents blade velocity
- m subscript represents the axial direction
- theta subscript represents the tangential direction
- metal subscripts represents blade properties
- subscript 1 or 2 represents blade inlet and exit, respectively

To predict the effects of co-swirl and counter-swirl on blade row performance, the meanline code can be applied to the specific compression systems using required blade and annulus geometry and a set of loss and deviation correlations based upon cascade tests of NACA 65 Series blades and Double Circular Arc blades as reported in [12].

In a specific example, the meanline code was applied to a single rotor (Rotor 1B) [13] and calibrated to the experimental results so that an accurate representation of the clean inlet performance was assured. An inlet swirl representing 5 deg of angular deviation from straight flow in both a co- and counter-rotation direction was applied to the meanline inlet boundary condition.

The meanline code was used to recalculate each flow point with an inlet flow angle of plus or minus 5 deg from axial. That is, the flow was given an angular velocity in the direction of rotor rotation (co-swirl) or in the opposite direction of rotor rotation (counter-swirl), thus producing a circumferential swirl component to the inlet flow. The results of the co-and counter-swirl blade row analysis using the meanline code produce the new co- and counter-swirl rotor characteristics presented in Figure 15 together with the clean inlet rotor characteristics.

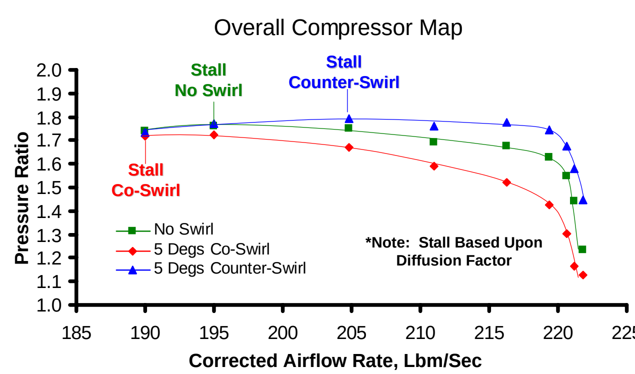


Figure 15. The Effect of +/- 5 Deg of Swirl on Rotor 1B Performance

The effect of a positive swirl angle (i.e., co-swirl) is to reduce the rotor pressure ratio at all flow points because there has been a reduction in the blade incidence angle. The reduction in total pressure ratio is more pronounced away from stall and near choke. The effect of negative swirl angle (i.e., counter-swirl) is to increase total pressure ratio at all flow points because there has been an increase in incidence angle.

To determine stall, classical diffusion factor calculations were made. Diffusion factors near or above 0.6 [14] are indicative of stalling behavior (flow separation resulting in under-turning of the flow) and has been used in the past to indicate stalled flow. Using that diffusion factor criteria, stall points were determined for both co-and counter swirl and are shown in Figure 15.

Parallel Compressor Analysis

A parallel compressor approach [6, 7] can be utilized to analyze compressor performance with circumferential inlet distortion. A one-dimensional modeling technique can be used for the analysis of distorted inflow via parallel compressor theory as illustrated in Figure 16.

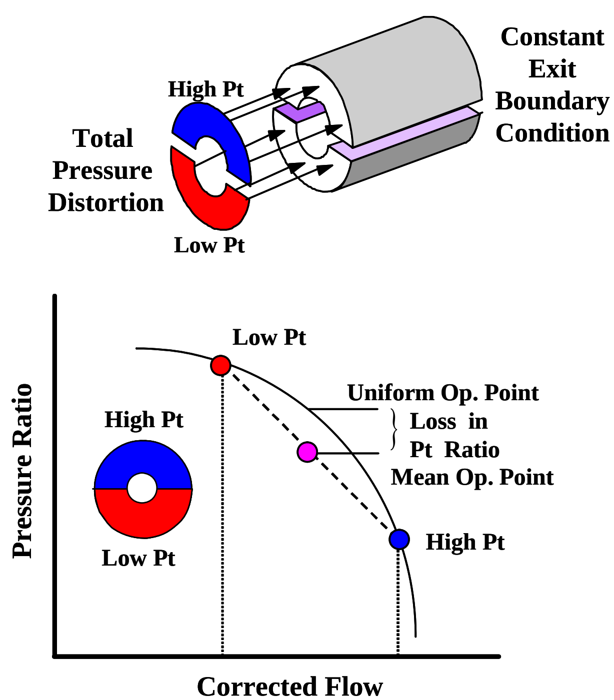


Figure 16. Parallel Compressor Modeling Concept

The overall compression system control volume is subdivided into a series of circumferential and parallel tubes. Each segment or tube then acts in parallel with each other segment, exiting to the same exit boundary condition. Different magnitudes of inlet total pressure and temperature can then be imposed upon each segment of the parallel compressor. In the purest sense, each segment is independent of all other segments, except through the exit boundary condition. System instability occurs when any one segment becomes unstable as a result of the inlet and exit conditions imposed upon it. For circumferential total pressure distortion, parallel compressor theory is generally valid if the segment arc is greater than 60 deg, also known as the critical angle. Secondary flow mechanisms become more significant for segments with arcs of less than the critical angle. The parallel compressor theory's predictive capabilities deteriorate when segments of less than the critical angle are used. Classical parallel compressor analysis uses nonswirl compressor stage characteristics to represent compressor response to the different sector inlet conditions, usually pressure and temperature only, with the boundary condition of uniform static pressure applied at the compressor exit.

For the parallel compressor approach to be utilized for the analysis of swirl, stage, blade-row or overall system maps must be generated that include the effects of swirl. These swirl maps will allow each of the different sectors of the parallel compressor containing different input swirls to operate at an appropriate operating point of the given off-design speed line. Thus the parallel compressor model will find the overall pressure ratio and corrected inlet flow of the composite operating flow and pressure rise on the basis of the sector input swirl and each parallel compressor operating point along a given speed line.

Using a parallel compression system numerical simulation, a parametric investigation was conducted to qualitatively determine the effects of both bulk and paired swirl on Rotor 1B compression system performance and operability [15]. Bulk swirl was investigated first to determine if the model would produce results similar to those obtained by the meanline code for both compression systems.

When twin-paired swirl was investigated, the parallel compressor simulation was divided into two equal circumferential segments. To simulate twin-paired swirl, one sector was required to use the co-swirl characteristics while the other sector was required to use the counter-swirl characteristics. When pressure distortion along with swirl was investigated, the same two circumferential segments were used, and one segment was reduced in inlet total pressure while the other was held at the initial pressure.

Similar to the bulk swirl case, twin-paired swirl was investigated with the parallel compressor model by applying the appropriate swirl compressor characteristic for each parallel tube. The results for Rotor 1B are presented in Figure 17. As can be seen, the twin-swirl performance in terms of Pressure Ratio is lower than both the no-swirl and counter-swirl bulk swirl cases. In addition, the stall point is between the counter and co-swirl cases. Comparisons of predicted performance between the parallel compressor and meanline codes (Figures 15 and 17) showed excellent agreement.

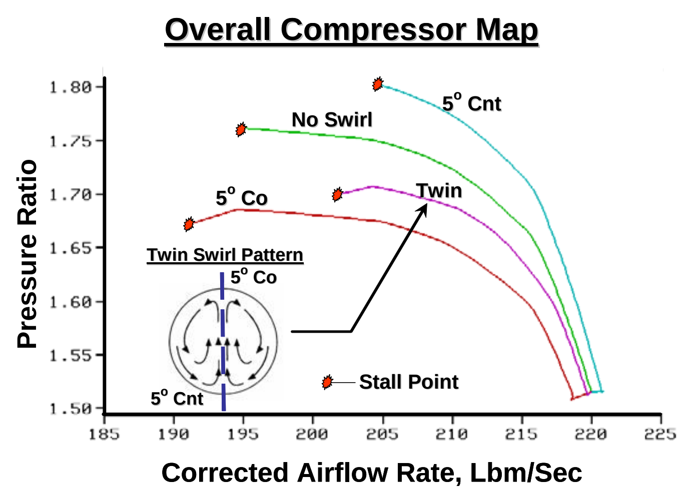


Figure 17. The Effects of Twin Bulk Swirl on Rotor 1B Performance and Operability

3D Euler Analysis

The two previous methods described are really one-dimensional techniques. In the case of the parallel compressor theory, the one-dimensional technique has been extended to a second dimension (circumferential direction) by virtue of an approximation. A fully three-dimensional technique is required to analyze inlet distortion that may have swirling flow. However, a fully viscous technique that relies on conventional CFD would have to solve a full annulus for many blade rows and would take a very long time even on today's massively parallel computers. Thus, to overcome some of the shortcomings of the meanline and parallel compressor approaches and provide more accurate, yet quick turnaround results, another approximate method has been developed by AEDC. That code is known as **TEACC** (**T**urbine **E**ngine **A**nalysis **C**ompressor **C**ode) [8]. The overall approach is depicted in Figure 18 and provides a measure of how the code is structured.

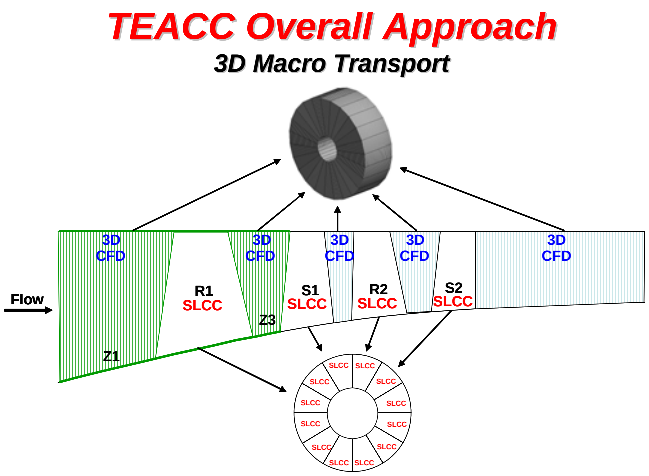


Figure 18. Overall TEACC Methodology

TEACC is a code that allows for the macro transport of distorted flow through the blade rows of a typical fan or compressor. Prior to, between blade rows, and after the last blade row, conventional CFD allows the transport of fluid properties via the Euler equations. Performance across each blade row is carried out by using a streamline curvature code that allows for radial distribution of flow properties. For circumferential variation during distorted flow, the SLCC code calculates a new radial distribution for each circumferential segment. The SLCC code allows for swirl and thus TEACC can handle swirl as well as total pressure distortion. An investigation was conducted to demonstrate the capability of TEACC for analyzing swirl [15]. A brief overview of that investigation is summarized in this paper to provide insight into the capability.

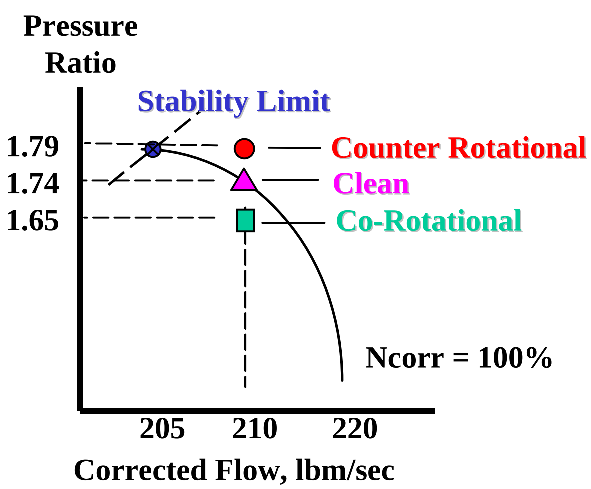


Figure 19. Comparison of Blade Overall Performance with Swirl at a Constant Airflow Rate

For that investigation, a bulk swirl component in a 90-deg segment was induced at the inflow boundary. Illustrated in Figure 19 are steady solutions at a constant mass flow rate of 210 lbm/sec with co-rotation and counter-rotation swirl of the same magnitude. This particular flow point represents a compressor operating point at 100 percent corrected speed at somewhat of a benign condition (i.e., away from stall and away from choke). As was expected, counter-rotation produced a more highly loaded blade.

Although these results were obtained for a fairly benign operating point, one can infer the effect on a point nearer to the stability limit. Counter-rotating swirl does indeed increase the loading on the blade and is most pronounced in the tip region. If the tip proves to be the area where stall inception takes place (a likely scenario for many of today's transonic fans), stall can occur at a lower flow rate than it would for a clean inlet. On the other hand, co-rotation will unload the tip and may enhance the system's stability margin. These results have been observed using the meanline and parallel compressor model and verify appropriate behavior from this technique.

SUMMARY

In a joint technology demonstration effort between AEDC and the USAF Academy, there is an opportunity to demonstrate the IT&E philosophy in pre-test, during test, and post-test modes. The joint effort proposes to use the USAF Academy F109 turbofan engine in an investigation to improve understanding of the effects of bulk or twin swirl on the fan compressor. The demonstration will use numerical predictions furnished by F109 fan models to aid in establishing the test matrix prior to the test, in identifying anomalies and qualifying data during the test, and in evaluating results after the test.

This demonstration will serve to enhance the awareness of test/analysis personnel as to the potential usefulness of the IT&E process and the role of modeling and simulation, and it will pave the way for implementing an IT&E process for operability at AEDC.

REFERENCES

1. SAE S-16 Committee, ARP 1420, Revision B,"Gas Turbine Inlet Flow Distortion Guidelines," Society of Automotive Engineers, February 2002.
2. SAE Aerospace Information Report AIR-1419, "Inlet Total-Pressure Distortion Considerations for Gas Turbine Engines," May 1983.
3. SAE S-16 Committee, ARD50026, "A current Assessment of Planer Waves," Society of Automotive Engineers, September 1995.
4. Society of Automotive Engineers, "A Current Assessment of the Inlet/Engine Temperature Distortion Problem," Aerospace Resource Document ARD50015, 1991.
5. Beale, D. K., Cramer, K. B., and King, P. S., "Development of Improved Methods for Simulating Aircraft Inlet Distortion in Turbine Engine Ground Tests," AIAA 2002-3045, 22nd AIAA Aerodynamic Measurement Technology and Ground Testing Conference, St. Louis, Missouri, June 24-26, 2002.
6. Davis, M., Jr., "Parametric Investigation into the Combined Effects of Pressure and Temperature Distortion on Compression System Stability," AIAA-91-1895, June 1991.

7. Shahrohki, K. A., and Davis, M. W., Jr., “Application of a Modified Dynamic Compression System Model to a Low-Aspect Ratio Fan: Effects of Inlet Distortion,” AIAA-95-0301, January 1995.

8. Hale, A. A., and O’Brien, W. F., “A Three-Dimensional Turbine Engine Analysis Compressor Code (TEACC) for Steady-State Inlet Distortion,” ***Journal of Turbomachinery*****,** Vol. 120, July 1998, pp. 422-430.

9. Rouser, K. P., Boyer, K. M., and Byerley, A. R., “A Contextual Framework for Enhancing an Undergraduate Thermo-Propulsion Sequence,” ASME Paper No. GT2006-90477, May 2006

10. Vining, C., Arnold, S., Hayes, B., and Howard, R., “PC-Based Generation 4 Non-Contact Stress Measurement System,” Proceedings of the 10th National Turbine Engine High-Cycle Fatigue Conference, March 8-11, 2005, New Orleans, LA.

11. Smith, S. L., “1-D Meanline Code Technique to Calculate Stage-by-Stage Compressor Characteristics,” M.S. Thesis, University of Tennessee, Knoxville, TN, 1999.

12. Hearsey, R.M., *Program HT0300, NASA 1994 Version*, The Boeing Company.

13. Seyler, D. R., and Gestolow, J. P., “Single Stage Experimental Evaluation of High Mach Number Compressor Rotor Blading, Part 2: Performance of Rotor 1B,” NASA-CR-54582, September 1967.

14. Cumpsty, N. A., ***Compressor Aerodynamics*****,** Longman Scientific & Technical, 1989, pp.47-48.

15. Davis, Milt, Hale, Alan, and Beale, Dave. “An Argument for Enhancement of the Current Inlet Distortion Ground Test Practice for Aircraft Gas Turbine Engines,” ***Journal of Turbomachinery***, April 2002, pp. 235-241.